Chapter 23 – How Big is Our Universe?

The contemplation of things as they are, without error or confusion, without substitution or imposture, is itself a nobler thing than a whole harvest of invention.

--Francis Bacon

In the space of one hundred and seventy-six years the Lower Mississippi has shortened itself two hundred and forty-two miles. That is an average of a trifle over one mile and a third per year. Therefore, any calm person, who is not blind or idiotic, can see that in the old Oolitic Silurian Period, just a million years ago next November, the Lower Mississippi River was upward of one million three hundred
thousand miles long, and stuck out over the Gulf of Mexico like a fishing-rod. And by the same token any person can see that seven hundred and forty-two years from now the Lower Mississippi will be only a mile and three-quarters long, and Cairo and New Orleans will have joined their streets together, and be plodding comfortably along under a single mayor and a mutual board of aldermen. There is something fascinating about science. One gets such wholesale returns of conjecture out of such trifling investment of fact.

--Mark Twain, Life on the Mississippi (1875)

Chapter Preview

In this chapter, we will attempt to answer the question, "How big is our Universe?" Measuring the distances to astronomical objects is one of the most difficult, mundane, and surprisingly fruitful enterprises of the astronomer. It leads naturally to the discovery of the answers to questions regarding the size of our Universe, and in the 20th century has
surprised astronomers with measurements that tell us much more about our Universe. As seen everywhere in the scientific enterprise, measurements that answer one question usually lead to many more.

Key Physical Concepts to Understand: *standard candle and standard meter stick methods for distance determination, variable stars, and the Hubble relation*

I. Introduction

One of the most fundamental yet difficult measurements in astronomy is the measurement of the distance to a remote object.

Without distance determinations, we are only able to view our Universe in two dimensions, as it appears projected onto the sky. In order to construct a conceptual 3-dimensional model of our galaxy, our Local Group, the local supercluster, or the Universe as a whole, it is essential that we are able to measure, or at the very least estimate, the distances to stars and galaxies.
There are four basic types of techniques currently used to determine the distances to astronomical objects: radar ranging, parallax, **standard candle techniques**, and **standard meter stick techniques**. The first two (Chapter 17, Section II) are quite specific and are limited to relatively nearby objects; the latter are categories that encompass a variety of related methods.

II. Standard Candle Techniques

![Figure 2. Photo of cars on a freeway at night.](image)
Newton quote about the uniformity of nature.

A standard candle technique is any distance measurement or estimation method that depends on the inverse square law of light: objects of known luminosity have a predictable brightness when they are placed at a given distance from an observer (Figure 1).

This method is one that can be used to estimate the distance to a light at night. If we are camping and we see the flashlight of another camper, we can estimate its distance by assuming that flashlights have a single luminosity (Figure 2). This assumption is not strictly true, different flashlights will have different luminosities depending on their model, age, the voltage fed to them, and just random flashlight-to-flashlight variations, not to mention the fact that we might be looking at a lantern and not a flashlight. If we know beforehand that our fellow camper is carrying a flashlight and not a lantern then we might make the judgement that most flashlights have luminosities within a certain range, and that range is small enough to allow us to make a crude distance estimation. Judging distance from flashlight brightness is just one example of a standard candle technique.

Mathematical Illustration of the Standard Candle Technique

Assume that we are discussing two main sequence stars of the same spectral type. Star A is 10 light-years away. Star B is at an unknown distance but
appears 100 times fainter than Star A. How far away is Star B?

The brightness of objects, whether they are candles, flashlights, or stars, falls with the square of the distance (as given by the inverse square law of light, Chapter 5, Section VI). This can be stated in the form of a mathematical equation:

\[ \text{Brightness} = \frac{\text{constant}}{\text{Distance}^2} \]

For Star A and Star B we may write:

\[ \text{Brightness of A} = \frac{\text{constant}}{(\text{Distance of A})^2}, \]

and \[ \text{Brightness of B} = \frac{\text{constant}}{(\text{Distance of B})^2}. \]
Dividing the first equation by the second, we can determine the ratio of distances from the ratio of brightnesses, or vice versa:

\[
\frac{B_A}{B_B} = \frac{D_B^2}{D_A^2},
\]

where \(B_A\) and \(B_B\) are the brightnesses of Stars A & B, and \(D_A\) and \(D_B\) are their distances. In our case we know that \(B_A\) is 100 times \(B_B\) and that \(D_A\) is 10 light years, so that:

\[
100 = \frac{D_B^2}{(10 \text{ light years})^2}, \text{ or rearranging, } D_B^2 = (10 \text{ light years})^2 \times 100.
\]

\(D_B = \text{square root } ((10 \text{ light years})^2 \times 100) = 100 \text{ light years.}\)

The distance to Star B is 10 light years.
Standard candles used in astronomical distance determination include stars of constant luminosity (spectroscopic parallax), variable stars, supernovae, and galaxies. We will discuss each, in turn, below.

**Table 25.1: Standard Candle Distance Determination Methods**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Range of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectroscopic Parallax</td>
<td>1 million parsecs to edge of the Milky Way</td>
</tr>
<tr>
<td>Variable Stars</td>
<td>20 million parsecs most distant stars in nearby galaxies</td>
</tr>
<tr>
<td>Supernovae</td>
<td>100s of millions of parsecs to distant galaxies</td>
</tr>
<tr>
<td>Galaxy Luminosity</td>
<td>300 million parsecs to distant galaxies</td>
</tr>
</tbody>
</table>
Spectroscopic parallax.

- Using the standard candle technique in astronomy involves making assumptions about the intrinsic brightnesses of stars and galaxies.
- If we can determine that a distant star is a main sequence star of a certain temperature, then its luminosity can be determined from our knowledge of the Hertzsprung-Russell diagram, which relates luminosity to photospheric temperature (Figure 3).
- After measuring its apparent brightness, its distance can be determined from the inverse square law of light, which relates distance to the apparent brightness of an object of known luminosity.
- This method is called spectroscopic parallax; this term is somewhat misleading because it is not directly related to ordinary parallax, which is based on the use of a changing viewing geometry to triangulate the distance to an object (Chapter 17, Section II).
- Spectroscopic parallax is based on the ability of an astronomer to identify a star's temperature
and luminosity class (Chapter 17, Section IV), and thus determine its luminosity.

- This method is useful within the Milky Way. Beyond the Milky Way, individual main sequence stars are too faint to be useful as distance indicators.

Figure 3. H-R diagram sketch. Original.

Variable Stars.
Two of the most accurate and frequently used astronomical standard candles are the Cepheid and RR Lyrae variable stars (Table 23.2).

Both are stars in the post-main sequence stages of evolution (ref.).

Table 23.2: Characteristics of Cepheid and RR Lyrae Variables

<table>
<thead>
<tr>
<th></th>
<th>Cepheids</th>
<th>RR Lyrae variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (suns)</td>
<td>5-12</td>
<td>~1</td>
</tr>
<tr>
<td>Luminosity (suns)</td>
<td>100-10,000</td>
<td>100</td>
</tr>
<tr>
<td>Period</td>
<td>1-150 days</td>
<td>0.3-0.9 days</td>
</tr>
</tbody>
</table>

A precise relationship between the period and luminosity of Cepheid variables was discovered in 1912 by Harvard astronomer Henrietta Leavitt for
Cepheid variables in the Small Magellanic Cloud (Figure 4).

In 1924, Hubble used this work to determine the distance to the Andromeda galaxy and ended the debate about whether galaxies were internal or external to the Milky Way.

Because Cepheid variables are roughly 10,000 times the luminosity of the Sun, they are used to find the distances to galaxies millions of light years away.

Hubble then used this period-luminosity relationship for determining distances to more distant galaxies.
Figure 4. Cepheid variables. Panel A: The Period-Luminosity relation for Cepheids. P 377-22.16. Panel B: Hubble Space Telescope images of a Cepheid variable in M100. This color image is a Hubble Telescope Image of
RR Lyrae variables also have a period-luminosity law (Figure 5). RR Lyrae stars are low-mass Population II stars commonly found in globular clusters.

Because they are much fainter than Cepheid variables, with luminosities in the range of hundreds of solar luminosities, they are not useful for determining distances to other galaxies, other than a few nearby ones.

Nevertheless, they are of great use in determining the structure of our own galaxy. In 1915, Harlow Shapley used directions to Milky Way globular clusters along with distances measured by the RR Lyrae period-luminosity relationship to model the three-dimensional distribution of globular clusters in the Milky Way.

He found that they form a spherical system 100,000 light years in diameter centered on a point in Sagittarius (Chapter 21, Figure 5). He assumed that these outlined the true extent of the volume of the
Milky Way and determined that the Sun is not at the center of the galaxy.

This enables astronomers to determine distances:

- Find the period.
  - This gives the luminosity.
  - Measure the apparent brightness.
- Determine the distance from the luminosity and brightness.

**Figure 5. Period-luminosity relationship for Cepheids and RR Lyrae stars and the recipe for using them to**
Web animation: Extragalactic Variable Stars

**Supernovae.**

- In their earliest stages, supernovae can outshine an entire spiral galaxy of 100 billion stars, making them observable to distances of hundreds of millions of light-years.
- Supernovae are commonly used as standard candle distance indicators when they are near maximum brightness.
- This technique suffers from one drawback, supernovae only occur infrequently, typically once every 40 to 50 years in any given spiral galaxy.
- However, supernovae have been used as distance indicators out to more than 5 billion light years distance.
**Sc Galaxies.**

1. Although galaxies as a whole vary widely in luminosity ([Figure 6](#)), individual galaxy classes may have a reasonably small luminosity variation.
2. Elliptical galaxies and irregular galaxies in particular have wide luminosity ranges.
3. Sc galaxies have been used in determining the distance to distant galaxy clusters, where most other techniques lack sensitivity.

### III. Standard Meter Stick Techniques

- A standard meter stick technique is any distance determination technique that uses the apparent size of an object of known dimension to determine its distance.
- The angular size of an object decreases in proportion to its distance.
- A meter stick held perpendicular to the line of sight occupies an angle of 11 degrees at a
distance of five meters (Figure 7). When moved to a distance of 10 meters it will occupy an angle of only 5.5 Degrees. (For additional examples see Chapter 2, Section IV.) When driving we can and do estimate the distance to cars and people by how large they appear. In doing so we assume that cars and people come in reasonably standard sized packages. We can also estimate the distance to a faraway building by its apparent height and the distance to an intersection by the apparent width of the highway at the point of intersection (Figure 7).

- All standard meter stick distance determination/estimation techniques are based on the assumption that objects of an identifiable type (e.g. cars, people, and roads) have nearly the same size.
- Stars at any distance beyond the Sun are too small to use as standard meter sticks, but HII regions, the giant gas clouds ionized by O and B stars, and galaxies themselves have been used as standard meter sticks.
Figure 7. *Standard meter stick sketch.* Original.
Table 23.1: Standard Meter Stick Distance Determination Methods

<table>
<thead>
<tr>
<th>Technique</th>
<th>Range of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>HII Region Diameter</td>
<td>Nearby galaxies</td>
</tr>
<tr>
<td>Galaxy Diameter</td>
<td>To distant galaxies</td>
</tr>
</tbody>
</table>

IV. The Distance Determination Ladder

As shown in Figure 8, astronomical distance determination techniques form a distance determination ladder.

Each method depends on a method used for determining distances to more nearby celestial objects.
The Sun is 8 light minutes away. The next nearest star is 4 light years distant. The most distant quasars are as far away as 13 billion light years. We can’t use a single method for distance determination.

Radar is the most precise distance determination technique, but can only be used to find the distances to planets.

Knowing the distance from the Earth to the Sun, from radar ranging, we can determine the distance to nearby stars from the use of parallax, the amount of apparent shift that is seen for an object in the sky as the Earth orbits the Sun. In order to determine the distance that an object has from its parallax, we must already know the size of the Earth’s orbit; this is calculated by measuring the distance between the Earth and a number of other planets over a period of years.
**Figure 8.** The cosmic distance ladder. This chart shows a variety of methods of measuring the distances to celestial objects and the distances over which these methods are appropriate. The measurement errors, measured as a percentage, are larger for more distant objects. *P 563-31.34.*

**Step by Step:**
- Once the parallax method has been calibrated, it is in turn used to calibrate the method of spectroscopic parallax.
- Distances are determined to nearby stars of known spectral type using trigonometric parallax, which is viable out to a distance of about 500 light years.
- After the luminosity of a number of stars of each spectral and luminosity type have been determined, they can be used as standard candles.
- Each of the distance determination methods is useful over a limited range of distance.
- Larger and/or brighter objects must be found for use as standard candles or standard meter sticks for greater distances.
- Errors accumulate with each method used; therefore, distance determinations for distant galaxies may contain large accumulated errors.
- For distant galaxy clusters, in order to minimize the error associated with an individual measurement it is often desirable to measure the distances to many galaxies in the same cluster, all at the same distance. Then all of the galaxies
can be attributed the same distance, the mean of all the measures.

V. The Hubble Relation

• In 1923, more than ten years before Edwin Hubble had determined that Andromeda and, by inference, other galaxies were outside the Milky Way, V.M. Slipher of Lowell Observatory measured the velocities of 40 galaxies from the Doppler shifts of their absorption lines.
• These galaxies had large red shifts indicating velocities up to 1,800 km/s away from the Sun; none, but the nearby Andromeda galaxy, had a blue shifted spectrum, which would indicate velocities toward the Sun.
• In 1929, Hubble published a comparison of the velocities of these galaxies and their distance as estimated from photometry of Cepheid variables found in them.
A high degree of correlation was found between distance and velocity.

The red shift of a galaxy is proportional to its distance (Figure 10), except for variations at small distances caused by local effects such as the motion of galaxies in the Local Group toward the Milky Way and Andromeda.

This relationship is called the **Hubble law** and can be expressed as:

**Equation 25.1: velocity = H x distance,**

where H is a constant of proportionality now called the **Hubble constant**.

By induction, astronomers use the Hubble law to determine the distances to extremely distant galaxies for which little is known but the galaxy red shift.

In this way, the Hubble law is considered the final rung in the distance ladder.
<table>
<thead>
<tr>
<th>Cluster Nebula in</th>
<th>Distance in Light-years</th>
<th>Redshifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgo</td>
<td>78,000,000</td>
<td>H + K: 1,200 km s(^{-1})</td>
</tr>
<tr>
<td>Ursa Major</td>
<td>1,000,000,000</td>
<td>H + K: 15,000 km s(^{-1})</td>
</tr>
<tr>
<td>Corona Borealis</td>
<td>1,400,000,000</td>
<td>H + K: 22,000 km s(^{-1})</td>
</tr>
<tr>
<td>Bootes</td>
<td>2,500,000,000</td>
<td>H + K: 39,000 km s(^{-1})</td>
</tr>
<tr>
<td>Hydra</td>
<td>3,960,000,000</td>
<td>H + K: 61,000 km s(^{-1})</td>
</tr>
</tbody>
</table>
The bottom spectrum shown below is for hydrogen in the lab (where the speed of the object is $v=0$). The top spectrum is for hydrogen lines in a galaxy that is moving at four tenths of the speed of light away from us. As you can see, the lowest wavelength violet line gets shifted all the way up to the orange part of the spectrum.

Hubble Law

recession speed = $H_0 \times$ distance

![Graph showing the relationship between speed and distance.](image)
The change in the wavelength of a spectral line, $\Delta \lambda$, is defined as the shifted wavelength minus the wavelength as measured in the laboratory. That is, it's the difference between the wavelength measured when the object is moving and the wavelength measured if the object were at rest.

See also:

http://astro.wku.edu/astr106/Hubble_law_anim.gif
Figure 10. The Hubble relation. Panel A. On the left are elliptical galaxies in four galaxy clusters shown to the same scale. On the right are spectra of these galaxies showing their red shifts. A laboratory comparison spectrum is shown above and below the spectrum of each galaxy. The H and K lines of ionized calcium are seen in each galaxy spectrum; the yellow arrows show how far each set of galaxy lines has been red shifted. The velocity of each galaxy is shown below its spectrum. Its distance, in megaparsecs, is shown next to the image of each galaxy. P 560-31.30. Panel B: The Hubble diagram for the four galaxies shown in Panel A. P 561-31.31.

How do we account for the Hubble law? It is obvious that it is not somehow due to the random motions of galaxies or simply an effect of their gravitational attraction to one another, for nearly all galaxies are found to be moving away from the Milky Way. This relationship would not be expected to occur in a static, unchanging Universe, but could be expected to occur in an expanding one, in which all of space and the galaxies embedded in it are moving apart. This observation leads to a number of questions. If the Universe is expanding and we see all galaxies moving away from the Milky Way, is
the Milky Way at the center of the Universe? Is there any confirming evidence for such an expansion? What caused the expansion? We will study the theories of the Universe that physicists and astronomers have put forth to explain the Hubble law in Chapter 26 and look at the evidence that supports or denies these theories.

See also:
http://www.astr.ua.edu/keel/galaxies/distance.html

Summary

There are four basic techniques currently used to determine the distances to astronomical objects: radar ranging, parallax, standard candle techniques, and standard meter stick techniques. The first two are limited to relatively nearby objects. A standard candle technique is any distance measurement or estimation method that depends on the inverse square law of light; objects of known luminosity have a predictable brightness when they are placed
at a given distance from an observer. Standard candle methods include spectroscopic parallax, variable stars, supernovae, and galaxy luminosity. A standard meter stick technique is any distance determination method that uses the apparent size of an object of known size to determine its distance. Standard meter stick methods include HII region and galaxy diameter measurements.

Two of the most accurate standard candles are Cepheid and RR Lyrae variable stars. Both are post main sequence stars in the instability strip of the H-R diagram. These stars vary in brightness as their atmospheres alternately expand and contract. Their use as standard candles is predicated on the relationship between period and luminosity for each type. By plotting the distance vs. red shift of forty galaxies, Edwin Hubble determined that the Universe must be expanding in such a way that the observed velocity of a galaxy is proportional to its distance. This is the Hubble law.

**Key Words & Phrases**
1. **Cepheid variable** - a giant pulsating star with a period between 1 and 70 days. They are named for their prototype, Delta Cephei.

2. **Hubble constant** – the constant of proportionality in the Hubble law.

3. **Hubble law** – the law which states that the cosmological expansion velocity of a galaxy is proportional to its distance.

4. **standard candle technique** – any astronomical distance determination technique based on the inverse square law of light.

5. **standard meter stick technique** – any astronomical distance determination technique based on the concept that the apparent size of an object is inversely proportional to its distance.

6. **spectroscopic parallax** – the method of astronomical distance determination based on the use of spectroscopic classification of a star to infer its luminosity, followed by using its measured brightness to determine its distance.
Review for Understanding

1. How do we interpret the red shifts of galaxies? What does it tell us?

2. Why is the Hubble constant uncertain?

3. What is a standard candle technique for measuring distance?

4. What is a standard meter stick technique for measuring distance?

5. What measurements must be made of a star in order that its distance can be calculated by spectroscopic parallax?

6. Why is more than one standard candle technique necessary in astronomy?

7. Which distance indicators are more reliable, variable stars or Sc galaxies? Why?

Essay Questions
1. What assumptions are made in using Sc galaxies as a standard candle? How can these assumptions be verified?